Mortality and cancer morbidity in workers from an aluminium smelter with prebaked carbon anodes—part I: exposure assessment

Alf Rønneberg

Abstract

Objectives—To design a job-exposure matrix for epidemiological studies of men who had worked in a Norwegian aluminium smelter between 1922 and 1975.

Methods—Jobs held by cohort members were identified from personnel records. Tasks and their locations were determined for all jobs, and information was gathered about changes in exposure conditions over time. The jobs were combined into categories thought to have experienced similar exposure conditions, and time weighted average exposures were estimated on a relative scale. The results were reviewed by a panel of former smelter employees and an experienced industrial hygienist.

Results—96 different jobs could be identified from the cohort members' work histories. These were grouped into 18 categories, and relative exposure intensities were estimated for 31 different combinations of category and period. The most prevalent exposure in the cohort was pot emissions (fluorides, sulphur dioxide, and carbon monoxide; 74% ever exposed), followed by magnetic fields and heat stress (65–68%), asbestos (40%), and coal tar pitch volatiles (33%).

Conclusions—Although the use of this job-exposure matrix in the subsequent epidemiological studies may result in some misclassification of exposure, this is unlikely to seriously attenuate true risks in a stratified analysis based on cumulative exposure.

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Epidemiological studies based on retrospective exposure assessments have uncovered associations between cumulative exposure to coal tar pitch volatiles in the aluminium industry and the risk of bladder cancer^{1–4} and lung cancer.^{2,5} These results have concerned workers in smelters who have produced aluminium by electrolysis in cells or “pots” equipped with Söderberg anodes. In this type of anode a paste of petroleum coke and coal tar pitch is put in the top and baked continuously by heat from the electrolytic process. This leads to contamination of the workroom air with coal tar pitch volatiles or “tar” which

contain carcinogenic polycyclic aromatic hydrocarbons (PAHs).

The alternative “prebake” cells use anodes that have been baked in a separate building at 950–1200°C. This eliminates most of the coal tar pitch volatiles by evaporation or pyrolysis. Tar concentrations have therefore been negligible in prebake potrooms compared with Söderberg potrooms, but the two processes differ much less with respect to other exposures.

The objective of this investigation was to design a job-exposure matrix for an aluminium smelter that operated from May 1914 until April 1975 in Eydehavn, a small coastal township in southern Norway. The smelter included three potrooms where aluminium was produced in prebake cells, a foundry where the metal was cast into ingots, and an anode factory that produced prebaked carbon anodes for the potrooms. The job-exposure matrix was to be used in subsequent studies of cancer morbidity⁶ and circulatory and respiratory mortality⁷ in a cohort of 1137 men employed in 1922 or later. From the associations to be investigated in these studies, the exposure agents originally of interest were coal tar pitch volatiles, asbestos, pot emissions (fluorides, sulphur dioxide, and carbon monoxide), static and time-varying electromagnetic fields, and heat stress.

Methods

ASSESSMENT PROCEDURE

A historical job-exposure matrix for an industrial plant may characterise exposures by agent, job, area, and time.⁸ In our study this was accomplished by: (a) abstracting personnel records to identify all jobs held by the cohort members; (b) determining tasks and locations for all jobs; (c) obtaining information about exposure conditions in all tasks and areas over time; and (d) combining similarly exposed jobs into exposure categories and estimating time weighted average (TWA) exposure intensities on a relative scale. This approach was similar to that used in an assessment of historical exposures to formaldehyde by Stewart and coworkers,⁹ except that the lack of appropriate industrial hygiene data in our study prohibited the estimation of absolute exposure concentrations.

After standardisation of the nomenclature used in the personnel records, departments, sections, and job titles used in the cohort members' work histories were identified. The department was known for all but three of the

The Cancer Registry of Norway, Institute of Epidemiological Cancer Research, Montebello, N-0310 Oslo, Norway
A Rønneberg

Correspondence to:
Dr A Rønneberg, The Cancer Registry of Norway, Institute of Epidemiological Cancer Research, Montebello, N-0310 Oslo, Norway.

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cohort members' 2747 employment periods. A job was defined as a unique combination of department, section, and job title. The tasks that made up each job were described in terms of their approximate weekly duration, the use of materials and equipment that might cause exposure to one of the agents of interest, and the area in which each task was performed. Sources of exposure and the weekly duration of emissions in each area were also described, together with changes in work practices, processes, and control measures that might have influenced exposures in tasks or areas. These data were obtained through interviews with 10 employees who had started work between 1924 and 1942 and stayed employed until 1975, an industrial hygiene survey of the potrooms in 1962,¹⁰ the owner company's 50 year anniversary account,¹¹ and Labour Inspectorate documents concerning the smelter from 1963 to 1975.

The jobs were grouped into a smaller number of categories with similar exposures. This grouping was primarily based on the fraction of working hours spent in exposed areas, but some additional categories were defined due to exposures that originated from the performance of certain tasks. The criterion for a job to be classified as exposed was based on the average weekly duration of exposure. For heat stress and magnetic fields this was set at most of the working days, for coal tar pitch volatiles and pot emissions at least one day a week, and for asbestos at least one task a week that may have entailed dust exposure.

In the absence of industrial hygiene data, TWA exposures were estimated on a relative scale. For each agent a value of 1.00 was assigned to the highest level for any category at any time. This level was used as a reference when estimating exposures in the remaining combinations of category and period. The estimates were primarily based on the weekly duration of exposure, and then on subjective estimates of the intensity in different locations and the effect of changes in work practices, processes, or ventilation.

The work history of some cohort members included employment where only the department was known. Former employees were asked to identify the specific section and job for those employed in a potentially exposed department for at least one year after 1935. If this proved unsuccessful the employment was assigned to a non-specific category. Each non-specific category was given a weighted average of the exposures assigned to the specific categories, and this was based on the average number of men employed in each specific category at the beginning of each decade.

A panel of the 10 former employees reviewed a detailed description of jobs, their grouping into exposure categories, and their mutual ranking with respect to average intensity of exposure to each agent. This description and the relative exposure estimates were also reviewed by an industrial hygienist with long experience in the Nordic aluminium industry.

Analysis

The cohort's exposure experience was described through the number of men in each exposure category and the number of men ever exposed to each agent. Some of the dose-response relations to be investigated in the subsequent studies involved one outcome and two or more agents, and the presence of associations between these exposures was therefore of interest. These were: lung cancer and exposure to tar, asbestos, or pot emissions; urinary tract cancers and exposure to tar or heat stress; circulatory diseases and exposure to tar or pot emissions (carbon monoxide); and cancers of haematopoietic tissues or brain and exposure to static or time-varying magnetic fields.

Cumulative exposure was chosen as a surrogate for dose and calculated for each person-year under observation, and the presence of associations between pairs of exposures was therefore investigated within the cohort's person-time. The unexposed person-years were assigned to one stratum and the exposed person-years divided between a low and a high stratum, with the dividing point so that the two exposed strata included a roughly equal amount of person-time. Associations were described by cross tabulating the cohort's person-time by the ordinal cumulative exposure strata. For each pair of agents Gamma (Γ) was used as a measure of the association's strength and was calculated with BMDP statistical software.¹²

EXPOSURE CATEGORIES

After standardisation of nomenclature, nine different departments with a total of 16 sections and 66 job titles could be identified from the cohort members' work histories. From this 96 different jobs were defined, and these were grouped in 18 categories thought to have given rise to similar exposures.

Anode factory

The anode factory produced baked carbon anodes from 1918 to 1975. It was made up of three sections: the coke mill; the anode paste mixers and presses; and the anode baking furnaces. These were located in separate workrooms without any mechanical room ventilation, and there was no rotation of workers between them.

The *mill workers* were exposed to coke dust during the processing of petrol coke by calcination and milling. From the 1940s to 1968, they were also exposed to coal tar pitch dust during the crushing of pitch lumps with hand held vibration hammers. Three of the six coke mill workers were engaged in this work daily. This suggests that workers in this category may have been occupied with pitch crushing 25–50% of their working hours.

The *mixer and press workers* worked in a room where ground coke was mixed with molten pitch (16–20%) at 150–160°C in unhooded mixers. The hot anode paste was shovelled into forms and compacted into blocks with hand held vibration tools. Due to the high temperature of the paste, coal tar

pitch volatiles escaped from both mixers and press forms, and workers in this section were subject to continuous exposure to tar. Emissions were reduced in 1952 when mixers with exhaust ventilation and hydraulic compaction presses were installed, all with closed feeding equipment. The section employed 10–15 mixer and press operators and two fitters.

The *furnace workers* were responsible for the baking of anode blocks. A furnace was assembled for each batch of 200 tonnes, piling the blocks in a string on a refractory brick base. The string was covered with ground coke inside steel covers erected along the sides and top, with asbestos cord for sealing. A direct current of 10–12 kA was applied to the string, reaching a peak temperature of 950°C after four to five days. The furnace was allowed to cool before the assembly was dismantled. The annual production volumes corresponded to an average of one batch per week.

From 1918 to 1924 the two furnace bases were situated at the end of one of the potrooms. In 1924 a separate building was erected with eight furnace bases, and the furnace covers were connected to exhaust ventilation to reduce emissions. Still, large amounts of coal tar pitch volatiles escaped into the workroom, particularly during the first two days of each baking cycle. As late as 1970 the local Labour Inspectorate commented that the tar fumes led to reduced visibility and made it difficult to breathe inside the furnace building. Although spending most of their time assembling and dismantling cold furnaces, the 20–30 workers were exposed to emissions from the furnace currently under heating as all eight furnace bases were located within the same workroom.

Electrolysis

The electrolysis department included the three potrooms, in which potlining took place. Metal casting, and anode rodding were located in separate workrooms.

Potroom I started production in 1914 and potrooms II and III in 1916 with a total of 130 electrolytic cells. These consisted of a carbon lined steel vessel containing alumina (Al_2O_3) dissolved in molten cryolite (Na_3AlF_6) at 950°C. The carbon lining served as the cathode, and the anode was made up of prebaked carbon blocks suspended in the molten bath from a beam. The cells were operated at a voltage of 4.5 V and a direct current of 20 kA. In 1955 the current was increased to 25 kA and further to 34 kA around 1970. Fluorides, sulphur dioxide, and carbon monoxide were continuously emitted from the cells. A static magnetic field was generated by the direct current, but a time-varying field was also present as the incoming alternating current was not completely rectified.

Air exchange in the potrooms was maintained through roof apertures and wall slits at floor level. Roof exhaust fans were installed in the late 1950s, and the wall slits were enlarged around 1970. On hot summer days, the

potroom air temperature exceeded 70°C as measured with a conventional mercury thermometer.

The *potroom workers* and *tappers* spent a similar fraction of their working hours inside the potrooms and working directly on the pots. Their work was mainly performed manually until 1954, when roof cranes and several mechanical tools were introduced. These included pneumatic tapping crucibles with an asbestos gasket that had to be changed daily, so the tappers were therefore defined as a separate category with potential exposure to asbestos dust. The smelter employed 100–130 potroom workers and 12–13 tappers.

Although the *potlining workers* spent a similar fraction of their working hours inside the potrooms as potroom workers and tappers, they were assigned to a separate category due to their handling of pitch paste and asbestos in some tasks. Their work consisted of demolishing and rebuilding used pots while the pot was in the potline. The steel vessel was lined with asbestos board and prebaked carbon blocks, and a hot pitch paste was used to fill grooves between the blocks and to build up the pot's side lining. Iron bars connecting the pot to the current were insulated from the steel vessel with asbestos cement mixed at the work site. When a used cell was demolished, the asbestos lining was broken up and removed. The nine to 12 potlining workers demolished and rebuilt an average of one pot a week. All participated in the tasks that involved handling of asbestos and hot pitch paste and were exposed to these two agents six to eight hours weekly.

Maintenance

Of the workers in the mechanical maintenance section, the 20–25 *fitters* usually spent two to three days a week working in the potrooms and were exposed to the potroom atmosphere during this time. The *workshop mechanics* spent most working hours in the workshops and included six to nine turners, forgers, vehicle mechanics, and sheet metal workers. A few of the fitters were plumbers and may have been subject to considerable asbestos exposure, and this was also the case for two to three turners and sheet metal workers who used asbestos in the manufacture of tapping and casting equipment for the foundry after 1954. It was impossible to identify the men who had held these positions, and all fitters and workshop mechanics were therefore regarded as potentially exposed to asbestos.

The power supply section included rectifiers that converted alternating current at 25 or 50 Hz to direct current for the potlines, and the eight *rectifier workers* were exposed to both static and time-varying electromagnetic fields. The six to 10 *electricians* were responsible for all electrical installation and maintenance and may have been exposed to time-varying electromagnetic fields during this work. Each electrician worked about one day a week inside the potrooms and was exposed to pot emissions during this time.

The 10 to 20 *joiners* employed in the smelter's joinery section maintained housing quarters and plant buildings and have probably been subject to occasional asbestos exposure when working with boards containing asbestos used for fire proofing or heat insulation.

Supervisors

The 10 to 15 *potroom supervisors* spent about 25–50% of their working hours in the potroom, particularly during process irregularities that might lead to increased emissions from the pots. The six to seven *anode factory supervisors* probably spent a smaller fraction of their time in areas exposed to tar, mainly in the furnace section. Supervisors in other departments were assigned to the unexposed category.

Unexposed workers

The *unexposed* category included those workers who did not fulfil the criteria for being exposed: workers in casting, anode rodding, laboratory, and storage; quay construction, and saw mill workers; house painters and gate keepers; and administrative, technical, and mercantile staff. The number of employees in this category increased from 35 in 1920 to around 80 in the 1960s.

RELATIVE EXPOSURE INTENSITIES

Coal tar pitch volatiles

Tar exposure was largely confined to the anode factory. The smelter used hard coal tar pitch that typically contains around 14% PAHs. The pitch volatiles encountered in potrooms with Søberberg anodes may contain 15–55% PAHs,¹³ some of which are recognised carcinogens. In anode factories these constituents make up a smaller proportion of the total coal tar pitch volatiles than in Søberberg potrooms.^{3,13} This observation originates from plants with anode ovens heated by combustion of fuel oil and tar volatiles, and it is not known whether it also applies to electrically heated ovens such as those in the present smelter.

Former employees described the exposure intensity as higher at the furnaces than in the mixer and press section. This comparison was based on conditions after the changes were implemented in the mixer and press section in 1952. Whereas the heaviest exposures at the furnaces occurred for two days weekly, but were present all the time in mixing and pressing, and the relative levels may have been misjudged because of the presence of irritant gases such as sulphur dioxide in the furnace section. A level of 1.00 was therefore assigned to both categories before 1952, whereas the changes in that year were assumed to have reduced exposure to 0.50 in the mixer and press area. The mill workers and anode factory supervisors were assigned to a relative level of 0.10 as both probably spent most of their time in unexposed work.

The potlining workers were exposed during the handling of pitch paste as were the workers in the mixer and press area during com-

paction of anode blocks, but exposure took place for only six to eight hours a week in a larger room with a larger volume. The relative exposure in this work was therefore estimated to be 0.25.

Asbestos

The main asbestos supplier delivered only Finnish anthophyllite products and the other delivered mainly chrysotile products, and there is no evidence that crocidolite was ever used. From the late 1930s the annual consumption was 20 000–30 000 kg of asbestos board, 500–1500 kg of short fibred loose asbestos, and 300–500 m of asbestos cord. The loose asbestos and more than 95% of the board were used in potlining, whereas cord was used by furnace workers and metal tappers.

Potlining workers were by far the most heavily exposed to asbestos as they seem to have been exposed to asbestos dust for six to eight hours a week. Relative to this the furnace workers and tappers were assigned to a level of 0.10, and fitters, electricians, and joiners to 0.05.

Pot emissions

In 1962 exposures to fluorides, sulphur dioxide, and carbon monoxide in the potrooms were measured.¹⁰ Based on results from time studies and stationary samples taken near the breathing zone during each task, TWA exposures for both potroom workers and tappers were measured at 1.5–2.7 mg/m³ total fluorides, 43–47 ppm carbon monoxide, and 1.8–2.1 ppm sulphur dioxide. Fluorides were sampled on a Millipore AA filter and were then washed in two gas bottles with an unspecified absorbing solution; the analytical method was not stated. Carbon monoxide and sulphur dioxide were measured with direct reading indicator tubes.

Potroom workers and tappers were given relative levels of 1.00 from 1922 to 1954, 0.75 from 1955 to 1964, and 0.50 from 1965 to 1975. These reductions in exposures were primarily based on the subjective judgment by former employees, but are also supported by the probable effects of mechanisation of the work around 1955, and the installation of exhaust roof fans in the late 1950s and enlarged wall apertures in the late 1960s. Potlining workers and potroom supervisors were given a level of 0.50 from 1922 to 1964, and 0.25 from 1965 to 1975. The fitters' exposure was estimated to be 0.25 and the electricians' 0.10, according to the average time spent in the potrooms by these two categories.

Electromagnetic fields

Static and time-varying magnetic fields were present in the potrooms as direct current used in the potlines had not been completely rectified. According to experience from other Norwegian smelters,¹⁴ the exposures may be expected to have been roughly proportional to the ampérage of the electrolytic cells, but were also influenced by the daily time spent near

Table 1 Exposure matrix for the smelter from 1922 to 1975

Exposure category	Period	Change in exposure conditions	Tar	Asbestos	Pot emissions	Heat stress	Magnetic fields	
							Static	Time-varying
Anode factory:								
Mixer and press worker	1922–51	Manual feeding, no ventilation	1.00	—	—	—	—	—
	1952–75	Closed feeding, exhaust ventilation	0.50	—	—	—	—	—
Mill worker	1929–39	No handling of pitch	—	—	—	—	—	—
	1940–68	Crushing of pitch	0.10	—	—	—	—	—
	1969–75	No handling of pitch	—	—	—	—	—	—
Anode paste worker NOS (mixer, press, or mill)	1922–51	(as mixer and press worker)	1.00	—	—	—	—	—
	1952–75		0.50	—	—	—	—	—
Furnace worker	1922–75	No significant change	1.00	0.10	—	—	—	—
Anode factory supervisor	1922–75	No significant change	0.10	—	—	—	—	—
Anode factory worker NOS (anode paste or furnace)	1922–51	(average of the mixer and press and furnace categories)	1.00	0.05	—	—	—	—
	1952–75		0.75	0.05	—	—	—	—
Electrolysis:								
Potroom worker	1922–54	Manual work	—	—	1.00	1.00	1.00	0.10
	1955–64	Mechanisation	—	—	0.75	0.75	1.00	0.10
	1965–75	Room ventilation	—	—	0.50	0.75	1.00	0.10
Potlining worker	1922–64		0.25	1.00	0.50	0.25	1.00	0.10
	1965–75	Improved ventilation	0.25	1.00	0.25	0.25	1.00	0.10
Tapper	1922–54	Manual work	—	—	1.00	1.00	1.00	0.10
	1955–64	Mechanisation	—	0.10	0.75	0.75	1.00	0.10
	1965–75	Room ventilation	—	0.10	0.50	0.75	1.00	0.10
Potroom supervisor	1922–64		—	—	0.50	—	0.50	—
	1965–75	Room ventilation	—	—	0.25	—	0.50	—
Electrolysis worker NOS (potroom, potlining, tapping, casting, or anode rodding)	1922–54		—	—	1.00	1.00	1.00	0.10
	1955–64	(as potroom worker)	—	—	0.75	0.75	1.00	0.10
	1965–75		—	—	0.50	0.75	1.00	0.10
Maintenance:								
Fitter	1922–75	No significant change	—	0.05	0.25	—	—	—
Workshop mechanic	1922–75	No significant change	—	0.05	0.25	—	—	—
Electrician	1922–75	No significant change	—	0.05	0.10	—	—	0.10
Rectifier worker	1922–75	No significant change	—	—	—	—	0.50	1.00
Power supply worker NOS (electrician or rectifier)	1922–75	(average of the electrician and rectifier categories)	—	—	0.05	—	0.25	0.50
Joiner	1922–75	No significant change	—	0.05	—	—	—	—
Unexposed jobs, various departments	1922–75		—	—	—	—	—	—

the pots, which decreased after mechanisation of the potroom work in the 1950s, when cell ampèreage increased from 20 to 25 kA. It was therefore impossible to estimate the change in TWA exposure to magnetic fields.

Based on the measurements performed in other smelters¹⁴ static field exposure was assessed as 1.00 for potroom workers, tappers, and potlining workers, and as 0.50 for potroom supervisors and rectifier operators. Exposure to time-varying fields was assessed as 1.0 for rectifier operators and 0.10 for potroom workers, tappers, potlining workers, and electricians. Rectifier operators may have been exposed to electrical fields, but such exposure was negligible in the potrooms, due to the low voltage of 4.5 V.

Heat stress

As with exposure to pot emissions, the average exposures to heat stress must have decreased with the mechanisation of potroom work in the mid-1950s. Heat stress was primarily associated with heat radiation from the pots and was probably not much influenced by changes in ventilatory conditions. The relative exposures of workers and tappers in pot-

rooms was therefore set at 1.00 before 1955 and at 0.75 between 1955–75. The relative exposure of potlining workers was estimated to be 0.25 as they usually did not work on hot cells.

Non-specific exposure categories

The *anode paste worker* not otherwise specified (NOS) category included workers who might have been employed in the mixer, press, or mill section, whereas the *anode factory worker* NOS category included men employed in these or the furnace sections. More than 80% in the anode paste area seemed to have been mixer and press workers, and the anode paste NOS category was given the same exposure values as this group. The number of anode paste workers seemed to be of the same magnitude as that of furnace workers, and exposure values for the anode factory NOS workers were taken as the average for the two specific categories.

The *electrolysis worker* NOS category was made up of potroom workers, tappers, potlining workers, and men employed in casting or anode rodding. More than 90% of the electrolysis workers had been employed in the

Table 2 Number of cohort members ever employed in each exposure category (employment-years in parentheses)

Exposure category	Total cohort	Men with ≥ 3 y total employment	Men with < 3 y total employment
Anode factory:			
Mixer and press worker	64 (379)	52 (359)	12 (20)
Mill worker	15 (120)	13 (118)	2 (2)
Anode paste worker NOS	36 (146)	21 (126)	15 (20)
Furnace worker	83 (678)	73 (662)	10 (15)
Anode factory supervisor	6 (114)	6 (114)	0 —
Anode factory worker NOS	144 (234)	83 (176)	61 (59)
Electrolysis:			
Potroom worker	207 (2184)	182 (2139)	25 (45)
Potlining worker	30 (375)	24 (367)	6 (8)
Tapper	26 (341)	24 (339)	2 (2)
Potroom supervisor	24 (316)	24 (316)	0 —
Electrolysis worker NOS	533 (1721)	253 (1304)	280 (417)
Maintenance:			
Fitter	108 (836)	68 (777)	40 (59)
Workshop mechanic	16 (260)	16 (260)	0 —
Electrician	24 (255)	18 (245)	6 (10)
Rectifier worker	17 (229)	17 (229)	0 —
Power supply worker NOS	8 (6)	3 (4)	5 (2)
Joiner	27 (322)	21 (309)	6 (13)
Unexposed jobs, various departments	246 (2729)	195 (2667)	51 (63)
Unknown	3 (11)	3 (11)	0 —
Total	1137 (11,257)	694 (10,522)	443 (735)

potrooms, and the electrolysis NOS category was therefore given the same exposure values as the potroom workers.

The *power supply worker NOS* category included rectifier operators and electricians. As the number of rectifier operators seemed similar to that of electricians, this category was given the average values of these two groups.

Results

The jobs held by the cohort members were assigned to 18 categories thought to have experienced similar exposures at any one time. The resulting job-exposure matrix included 31 different combinations of category and calendar year and 186 estimates of eight hour average exposures by agent,

category, and time. The employee panel recommended a change in two estimates, and the industrial hygienist suggested that 10 estimates should be changed. All these recommendations were followed, and table 1 shows the final matrix. This table also indicates events that were assumed to have led to a change in exposures.

Table 2 shows the number of cohort members by exposure category. In the epidemiological studies short term workers showed a high total mortality that seemed to be unrelated to exposures in the smelter. Detailed exploration of potential dose-response relations was therefore confined to the subcohort of 694 men with at least three years of employment, and the present analysis of the distribution of exposures and associations between them was confined to this group. Employment in the non-specific exposure categories constituted only 15% of the employment-years in this subcohort compared with 68% among the short term workers. Of the men with at least three years of employment 74% had at some time been exposed to pot emissions, 65–68% to magnetic fields and heat stress, 40% to asbestos, and 33% to coal tar pitch volatiles.

Table 3 shows cross tabulations of the cohort's person-time by the ordinal cumulative exposure strata for pairs of agents that might be associated with the same outcome. Positive associations were found between cumulative exposure to time-varying and static magnetic fields ($\Gamma = 0.80$) and to tar and asbestos ($\Gamma = 0.68$), whereas minor associations were present between tar and pot emissions ($\Gamma = -0.30$), tar and heat stress ($\Gamma = -0.22$), or between pot emissions and asbestos ($\Gamma = -0.07$).

Discussion

The performance of this job-exposure matrix in the subsequent epidemiological studies depends on its ability to distinguish between the truly exposed and unexposed workers. This will in turn depend on the quality of the

Table 3 Associations between pairs of exposures in the subcohort with at least three years: cross tabulation of person-years by cumulative exposure

		Asbestos		
		0	< 0.5	≥ 0.5
Coal tar pitch volatiles	0	10873	1549	1541
	< 3	952	1650	550
	≥ 3	798	916	1640
		Pot emissions		
		0	< 4.3	≥ 4.3
Coal tar pitch volatiles	0	2805	5488	5669
	< 3	644	1362	1146
	≥ 3	1672	973	709
	0	4999	4003	4960
		Heat stress		
		0	< 4.5	≥ 4.5
Coal tar pitch volatiles	< 3	986	1212	954
	≥ 3	1875	903	575
		Asbestos		
		0	< 0.5	≥ 0.5
Pot emissions	0	3161	919	1040
	< 4.3	4339	2336	1148
	≥ 4.3	5122	859	1543
		Time-varying magnetic fields		
		0	< 0.6	≥ 0.6
Static magnetic fields	0	6732	264	1949
	< 5.5	6	5688	235
	≥ 5.5	16	394	5183

work histories and to what extent the constructed categories may predict each person's exposure. Also, the performance of the matrix will depend on how closely the relative estimates of average exposures reflect true differences in exposures, and on how the estimates are used to develop measures of each person's dose.

The quality of the work histories was checked by using them to calculate the average number of men employed in each department and section at the beginning of each decade from 1920 to 1970. As the cohort included only men hired after 1922, this calculation was based on the smelter's personnel registry, which was thought to be complete for hourly salaried workers from 1918 and for staff workers from around 1940. The results compared well with independent estimates made by the panel of former employees for the period from 1940 to 1970, and the number of workers and supervisors in each department in 1962 was also in full agreement with data given in the industrial hygiene report from that year.¹⁰

The maintenance workers presented the most serious problem of misclassification of exposure. Whereas the electrolysis and anode factory workers were exposed mainly through their permanent workplace being in a contaminated workroom, most maintenance workers performed many tasks in several locations, and both tasks and workplaces may have entailed different exposures. Thus the fitters included both potroom crane repairmen with heavy and regular exposure to pot emissions, plumbers with considerable asbestos exposure, men with tar exposure from working in the anode factory, and some who may have spent most of their time in unexposed work.

Exposure to asbestos posed a special problem, as regular use of this substance was confined to the 24 potlining workers in the subcohort with at least three years of employment. The remaining 287 men who were classified as ever exposed to asbestos included fitters, workshop mechanics, electricians, joiners, metal tappers, and anode furnace workers whose exposures ranged from high to possibly negligible. The extent of misclassification may therefore be assumed to be larger for exposure to asbestos than to the other agents.

Some misclassification of exposure has also occurred due to the lack of detail in some work histories. When the number of workplaces in each department, section, and job according to the work histories was compared with the estimates from the panel of employees, this problem seemed to be limited to employment before 1950. From this comparison, the two NOS categories in the anode factory may have included no more than 5% of unexposed mill workers, whereas the electrolysis worker NOS category included less than 10% of unexposed casting and anode rodding workers, as well as less than 5% potlining workers exposed to asbestos. This source of misclassification also seemed to be of little importance in the subcohort with at least three years of employment, as only 15% of

their employment-years had been spent in a NOS category, compared with 68% among the short term workers.

Several jobs were classified as non-exposed. This is thought to be true for all agents defined originally as relevant, although quay workers, maintenance supervisors, and technical staff may have had infrequent exposures. Small groups had been exposed to solvents, oil mist, and soft wood dust, but the relevance of these exposures was regarded as questionable.

The ability of the matrix to identify the exposure of cohort members correctly might also have been described in terms of its sensitivity and specificity—that is the proportions of the truly exposed and truly unexposed workers who had been correctly identified as such. The sensitivity and specificity are based on a dichotomous exposure variable with the person as the unit of observation. It is difficult to interpret sensitivity and specificity in relation to the performance of the matrix in epidemiological studies based on a time related continuous exposure variable with person-years as the observation unit in a stratified analysis with more than two exposure strata.

Analysis of associations between pairs of agents showed positive associations between tar and asbestos and in particular between the two types of magnetic fields. Although not analysed here, one might also expect that for most of the agents under study cumulative exposure was positively associated with duration of exposure, as the reduction factors for exposure intensity over time or between categories were relatively small. These associations may be of importance when interpreting the results of the subsequent epidemiological studies.

In these studies, the relative exposure estimates will be used to calculate each worker's cumulative exposure for every person-year under observation. The cohort's person-years will then be stratified into one unexposed stratum and two exposed strata that include a roughly equal number of person-years. Misclassification of exposure is most common in the maintenance categories, and these have been given much lower relative exposures than the production workers. As a consequence the production workers will dominate the person-time in the higher cumulative exposure stratum, and attenuation of the observed risks in this stratum by non-differential misclassification of maintenance workers will probably not be a serious problem.

Misclassification may also result if the relative estimates do not reflect true differences in average exposures. As with the other misclassification problems, this will not depend on disease and will tend to bias any true associations between exposure and disease risk towards the null value.

The industrial hygiene data from 1962¹⁰ already referred to allows translation of the relative estimates for pot emissions into absolute TWA exposures. These results suggest that the average exposure of potroom

workers to fluorides from 1922 to 1954 was 2.8 mg/m³, 2.1 mg/m³ between 1955 and 1964, and 1.4 mg/m³ from 1965 to 1975, whereas corresponding values in these three periods were 60, 45, and 30 ppm for carbon monoxide and 2.7, 2.0, and 1.3 ppm for sulphur dioxide. Validation of these and the other relative exposure estimates is impossible, due to the absence of industrial hygiene measurements at the time.

Previous epidemiological cancer studies in the aluminium industry that have used exposure data have focused on exposure to tar.¹⁻⁴ The present study shows that whereas only one third of workers employed in a Norwegian prebake smelter had been exposed to tar or asbestos, most had received exposure to pot emissions, magnetic fields, and heat stress. Agents other than tar therefore deserve consideration in future studies of cancer or cause specific mortality in aluminium smelter workers. In particular, consideration of these agents may be more relevant to the present situation in this industry, as most smelters erected after 1960 have been of the prebake type with very low tar exposure.

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